TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 891

TRANSITION BETWEEN LAMINAR AND TURBULENT FLOW

BY TRANSVERSE CONTAMINATION

By Alex C. Charters, Jr.
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SUMMARY

Tests carried out on a flat plate in a low-turbu-
lence constant-pressure tunnel at GALCIT showed that
the transition between laminar and turbulent flow could
be caused in a normally laminar region by a process of
"transverse contamination" in that transition, started
at some point in a normally laminar layer by an external
disturbance, affected the adjacent laminar boundary layer
and spread laterally as the flow progressed downstream.
This lateral spread took place at an approximately con-
stant rate, which varied slowly with the velocity of the
main flow but which, once transition started, was inde-
pendent of the originating cause.

INTRODUCTION

The concept of boundary-layer transition is a very
complex one and still lacks a clear theoretical exposi-
tion. The only way of attacking this problem scientifi-
cally is by an experimental separation and investigation
of stream conditions affecting (or probably affecting)
the transition of the boundary layer from the laminar to
the turbulent state. The principal conditions known to
affect the transition point are:

1. The turbulence of the flow outside the boundary
   layer, for example, the turbulence character-
   istics of the wind tunnel in which the inves-
   tigation is carried out

2. The pressure gradient along the boundary surface.

3. The curvature of the boundary surface.

In the series of researches on this problem, spon-
sored by, and conducted with financial assistance from
the National Advisory Committee for Aeronautics, each of
these three principal effects is supposed to be separate-
ly investigated. The part under investigation at the
GALCIT is the effect of curvature on boundary-layer tran-
sition. The difficulty of this investigation is clear,
when it is remembered that, in order to obtain well-
defined conditions, the influence of the two other ef-
fects must be reduced to a minimum.

This research first seemed to promise excellent re-
sults, but the problem turned out to be even more com-
plicated than had been assumed. It was necessary to
investigate, improve, and even partly to develop an ex-
perimental procedure different from the one previously
used. For this reason, during the latter half of 1938
and all of 1939 a research on the boundary-layer transi-
tion along a flat plate was carried out in a small wind
tunnel of low-turbulence level. The investigation yielded
interesting results that undoubtedly have an important
bearing on the general aspects of the transition problem.
Although much of this material was presented in the paper
"Transition by Transverse Contamination" on January 25,
1940, at the Eighth Annual Meeting of the Institute of the
Aeronautical Sciences, it is herein published for the
first time.

Since the completion of the original text of this
paper, further studies of the subject have been made at
GALCIT. Observations concerning the results of the re-
cent studies are given in the appendix, which was written
by Dr. H. W. Liepmann.

The author wishes to express his thanks to the
National Advisory Committee for Aeronautics for the grant
under which this project was carried out. Also, he
wishes to thank Dr. Theodor von Kármán and Dr. Clark B.
Millikan for their inspiration, encouragement, and advice,
without which the carrying on of this project would have
been difficult indeed.

APPARATUS

The original experiments were made in the wind tunnel
described in reference 1. Technical difficulties encountered

in this wind tunnel made it desirable to repeat transi-
tion determinations under more carefully controlled con-
ditions. The experiments reported herein were carried
out on a stiff boundary plate centrally mounted in the
working section of a small tunnel used at the laboratory
for turbulence-correlation investigations. The flow in
this tunnel is steady, uniform, and of very low turbulence,
the isotropy of the turbulence being insured by a fine-
grained honeycomb placed in the entrance. A glass plate
of the finest plate glass obtainable was used as the
boundary surface. The leading edge of th plate was care-
fully sharpened. The inclination of the plate could be
slightly adjusted and the tunnel walls could be moved in
and out to give any desired pressure gradient.

The technique for determining transition was essen-
tially that of Professor B. M. Jones, wherein a small,
flat, total-head tube pressed against the boundary sur-
face is moved in a streamwise direction along the boundary.
A special carriage riding on the glass plate itself was
built for carrying the measuring instruments and held
them at a constant perpendicular distance from the surface
during a survey. The surveys were made by mounting the
instrument on the carriage at the desired distance from
the surface and moving the carriage along the surface by
an external track mechanism. The carriage carried a fixed
Prandtl pitot-static tube placed in the free stream so
that the pressure of the total-head tube in the boundary
layer could be balanced against the static pressure of the
stream and a direct measure of the dynamic pressure through-
out the boundary layer be obtained. With the total-head
tube pressed against the surface the dynamic pressure had
a low value in the laminar boundary layer decreasing with
increasing distance downstream. At a certain distance
from the leading edge the dynamic pressure suddenly in-
creased over a very narrow region, indicating a very def-
initely located transition to the turbulent regime. Be-
yond this region the dynamic pressure again decreased with
increasing distance downstream. Such a behavior of the
dynamic pressure at the wall is in complete agreement with
the findings of other investigators; also, since the pres-
sure at the wall is directly proportional to the shear
stress, our results are in agreement with theory.

RESEARCH PROCEDURE AND RESULTS

The usual preliminary adjustment of apparatus was made in order to control the state of the flow. The incidence of the plate was changed until a Reynolds number of transition of 1,800,000 (based on the free-stream velocity and the distance from the leading edge to the transition) indicated that a stable angle had been reached. The width of the working section was adjusted until the static pressure was constant to within 1/4 percent of the free-stream dynamic pressure over the length of the section. Transition surveys were carried out showing the dependence of transition on pressure gradient. The accuracy of adjustment was considered satisfactory because it was found that pressure gradients of the order of magnitude of 1/4 percent or less had no effect on the transition. All the preliminary adjustments were carried out at a single speed, close to the maximum obtainable in the tunnel. When these surveys were finished, determinations of transition were made at a series of speeds to test the similarity law. (See figs. 1 and 2.) The results definitely showed that the similarity law did not hold under the conditions of flow present in the tunnel. This result was a serious discrepancy from the predictions of the theory.

The pressure surveys indicated that transition tends to take place at a fixed distance downstream rather than at a fixed Reynolds number. This result gave a clue to the actual state of affairs in the boundary layer. It is well known that properties of the fluid which are carried by a turbulent transport mechanism diffuse at an angle that is relatively independent of the speed. Thus, if a disturbance on the top and the bottom of the tunnel started transition spreading across the surface, the transition region would have a V-shape, the angle of the V would change only slowly with speed, and transition along any particular line would stay approximately fixed in location.

The surveys up to this time had been confined to the center line of the glass plate. A survey was now made over the entire surface of the plate and, as predicted, the transition region was found to be V-shape. (See fig. 3.) The mouth of the V coincided closely with the leading edge of the plate and its apex lay on the center line. Surveys over a range of speeds showed that the angle and the location of the V changed but little, thus

accounting for the failure of the similarity law to apply
in this case. An inspection of the tunnel disclosed that
the joint between the contracting section and the working
section had not been carefully made; there was a misaline-
ment of nearly 1/8 inch on both the top and the bottom.
This misalinement created a very turbulent disturbance on
these surfaces, and this disturbance flowing past the
edges of the glass plate might easily have "contaminated"
the normal laminar layer and started transition spreading
across this layer. Other causes of the V-shape transi-
tion region were possible and these causes were eliminated
before study was made of conditions at the misalinement of
the entrance.

One possible cause existed in the great sensitivity
of transition to the inclination of the plate to the air
stream. The flow in the tunnel had not been carefully
investigated over the entire cross section prior to this
research, and it was possible that a nonuniformity in its
direction existed which would put the center of the plate
at a stable incidence and its edges at an unstable inci-
dence. Such a state of flow could be caused by a double-
vortex system. The axis of the vortices would be parallel
to the direction of flow; one vortex would be situated in
the upper half of the tunnel, the other vortex in the
lower half, and they would rotate in opposite directions
in accordance with the Helmholz law. Such a vortex pair
would incline the flow one way at the center and the
other way at the top and the bottom with a gradual change
of inclination from one to the other just as is required.

Any change in the direction of flow would appear as
a static-pressure gradient due to the centrifugal forces
involved; an extensive survey of the static pressure in
the forward part of the working section was therefore
carried out. This survey revealed static-pressure gradi-
ents that might have been due either to a double-vortex
system or to changes in cross-sectional shape caused by
the mounting strips on the top and the bottom. If the
gradients are caused by vortices, it is possible to com-
pute their strength and the resulting inclinations of
flow from the pressure surveys. Computations showed that
these vortices would be sufficiently strong to cause a
change in inclination of at least 15° from the center to
the edge. A careful investigation of the flow direction
with a fine streamer showed no such change. In fact,
as far as could be detected by the streamer (the method is

good to a few degrees), the flow over the entire working
section was uniformly parallel. This contradiction elimi-
nated the possibility that a double-vortex system was
present.

Another possible cause of the V-shape transition
region existed in the fact that the boundary layers on the
top and the bottom were in a very disturbed state, for it
was conceivable that their thickness increased as rapidly
as the spread of transition. In this case the line of
transition would merely be the line of demarcation on the
glass plate of the two boundary layers. Surveys were made
in planes parallel to the plate and spaced at different
distances for the purpose of locating the outer edge of
the boundary layer. These surveys are combined in the form
of a composite diagram (fig. 4) containing all the super-
imposed maps for the separate planes. The technique for
locating the limit of the boundary layer was simple. The
total pressure everywhere in the free stream was constant
but, immediately at the entrance to the boundary layer,
the total pressure started decreasing owing to the dissi-
pation of energy by the shearing forces. This knowledge
was utilized to find the limit of the boundary layer by
mounting a total-head tube a known distance from the sur-
face and moving it backward along the plate until its read-
ing started to decrease. In order to be more definite,
the tube was brought to that point where the velocity was
$99\frac{1}{2}$ percent of the free-stream velocity.

This survey eliminated the possibility that the V-
shape transition was merely the line of demarcation of
two boundary layers. As far downstream as 100 inches, the
boundary layer in the center is only $2\frac{1}{2}$ inches thick and,
as close as 1 inch from the plate, the boundary layer on
the mounting strip at 50 inches, the distance of the apex
of the V, is only $1\frac{1}{2}$ inches thick. The joining together
of the 1-inch lines farther downstream and the location of
the 1/2-inch line is due to the sudden rate of thickening
of the boundary layer on the glass plate after transition.

With those two possibilities eliminated, it was felt
desirable to investigate in greater detail the behavior
of the flow in the boundary layer.

First, the thickness of the boundary layer was meas-
ured over the entire surface of the plate. The results
are presented in the form of a contour map giving lines of
constant boundary-layer thickness. (See fig. 5.) In the

main, this map merely confirms the surveys on the location
of transition.   It does show that, insofar as thickness
is concerned, the laminar portion of the boundary layer
within the limits of the V is unaffected by the state of
transition at its edges. The presence of an undisturbed
region within the V is the result that would be expected
from the assumption that transition is propagated later—
ally by a turbulent—diffusion process.

    Second, an extensive three—dimensional survey of
turbulence was made over the length, the breadth, and the
depth of the boundary layer. Unfortunately, owing to a
reconstruction of apparatus, these measurements are not
so reliable as the other experimental data presented in
this paper. For purposes of comparison the turbulence
surveys should be satisfactory, but, as far as absolute
level of turbulence in concerned, they are questionable.
One survey of turbulence has been made before the recon—
struction was started and, by comparison with the later
measurements, a fair estimate could be made of the ac—
tual magnitude of the turbulence. (See fig. 6.) The
survey along a line 2 inches above the center line shows
the typical behavior of turbulence within the boundary
layer at different distances from the surface. (See
fig. 7.)

    The characteristics of the portion of the boundary
layer very close to the surface were of particular in—
terest. If the transverse contamination is carried by
the boundary—layer turbulence, a given rate of transport
will require a given magnitude of turbulence to support
it. It is assumed that the turbulence is isotropic and
that the cross—stream component is entirely responsible
for the lateral spread of transition. On this assumption
the root—mean—square of the velocity fluctuations (either
u' or v' as isotropy is assumed) divided by the local
velocity at the point in question is equal to the tangent
of the angle of spread. As the turbulence is defined as
the root—mean—square of the velocity fluctuations divided
by the local velocity, the boundary—layer turbulence in
a critical lamina will be equal to the tangent of the
angle of spread. The observed spread of $9\frac{1}{2}°$ would re—
quire 17—percent turbulence. In planes very close to
the surface where the turbulence is greater than the re—
quired 17 percent, the turbulence from the transition
should spread faster than the transition itself. The
uncertainty in the measurements of the absolute magnitude

of the turbulence combined with the fact that the level
of turbulence in the laminar boundary layer is not steady
makes the results seem uncertain in this regard. The
turbulence contours show the tendency for the turbulence
to diffuse more rapidly than the transition, however, and
they are significant because they show levels in the
boundary layer with sufficient turbulence to carry out the
lateral transport of transition at the observed rate.

In view of the good agreement between the transition,
the boundary-layer thickness, and the turbulence surveys,
it was thought advisable to put the hypothesis of trans-
verse contamination to a more rigorous test. If it is
assumed that this lateral contamination is a self-suffi-
cient process depending on an outside disturbance only
for a start, a critical test would be to change the nature
of the originating disturbance and then to observe the
behavior of the transition.

First, an attempt was made to eliminate the disturb-
ance insofar as possible by placing a false top a short
distance down from the real top of the test section.
(See fig. 8.) This false top was merely a thin flat
plate with a sharpened leading edge mounted perpendicu-
larly to the glass plate. Unfortunately, this attempt
was unsuccessful; for some unknown reason the presence of
the false top caused the flow at the leading edge of the
false top to be inclined sharply downward, a condition
that started a turbulent layer almost immediately on its
under surface and thus caused a disturbance along the
edge of the glass plate as severe as the disturbance from
the real top. The false top was moved from its initial
position 2 inches below the real top to a 4-inch position,
and finally to the center of the channel, in an attempt
to get away from this flow inclination, but without success.
Although this test did not give the expected results, it
is significant in that in all three locations of the false
top the transition region is V-shape in the same way as
before except that the V is smaller in size.

The originating disturbance not having been elimi-
nated, the test was carried to the opposite extreme, that
of adding an additional disturbance. This additional dis-
turbance was added in the center of the plate close to
its leading edge in the form of the wake from a small ob-
stacle. The obstacle was mounted perpendicularly to the
surface and extended across the tunnel. A similar obsta-
cle was placed on the opposite side of the plate to insure

symmetry of flow. A very clean joint was made between
the obstacle and the glass so that any disturbance must
have originated from the obstacle alone. The first obsta-
cle used was a 1/4-inch round rod. Behind such a bluff
body the wake represents, in the main, the energy dissipa-
tion of what is called form drag. This wake must be dif-
ferent in nature from the wake of a body having only what
is called profile drag. A second obstacle was therefore
used, this obstacle being a fine symmetrical airfoil set
at zero angle of attack. The wake and the transition were
measured for both obstacles. (See figs. 9 and 10.) The
results from these obstacle tests convincingly support the
hypothesis of lateral contamination. In both cases the
transition spreads out from the center, once it is started
by the wake of the obstacle, in precisely the same way
that it spreads from the top and the bottom. It would be
very difficult to attribute such a double-V transition
region to any other cause.

In addition, surveys with the airfoil obstacle in
place were made at two lower speeds. (See fig. 11.) In
their general characteristics the transition regions for
the three speeds are similar but the angle of diffusion
decreases slowly with decreasing speed, confirming the
previous results. The real physical significance of this
dependence on speed must, however, await a more extensive
investigation.

CONCLUSIONS

All the results lead to the conclusion that transi-
tion can be caused by a transverse contamination. In more
precise terms, a mechanism exists by which boundary-layer
transition can transport itself laterally across a surface.
The phrase "transport itself" has the significance that
the mechanism is self-sufficient and, once started, operates
independently from the disturbance that started it and
from the conditions in the external flow.

First, in all the wake and the transition surveys the
spread of transition was much more rapid than the spread
the motivating disturbance, in fact, the spread of the
transition was governed by a different law. On the top
and the bottom, the boundary-layer thicknesses increased
according to a logarithmic law. Behind both the rod and
the airfoil obstacles the wake thickness increased approxi-
mately as a narrow parabola. On the other hand, the

transition region spread linearly with distance at a con-
stant rate regardless of its originating cause. These
differences can be explained only by an independently
operating and self—sufficient mechanism governing the
spread of transition.

Second, the lateral spread of transition can be ex-
plained satisfactorily by the familiar turbulent trans-
port process. At transition the layers of the boundary
flow close to the surface undergo a violent increase in
velocity and an equally violent peak in turbulence. Such
a combination of sharp velocity gradient and drastic tur-
bulent agitation must surely generate and transport cor-
related vorticities of sufficient magnitude to upset com-
pletely the dynamic balance of the adjacent regions of
the boundary layer that they contaminate. Thus; if transi-
tion starts at any point on the surface, it will contami-
nate its neighboring regions of the boundary layer, these
in turn contaminate their neighboring regions, and so on
across the surface; so that transition will spread from
its source like a wave until it meets a solid boundary or
a turbulent layer. Also, this spreading process is ob-
served to take place at a constant rate, and such a linear
behavior is most indicative of turbulent diffusion.

The comparatively rapid rate measured by a $9\frac{1}{2}^\circ$ angle
of spread demands a word of explanation. On the assump-
tion of a turbulent transport mechanism, this rate of
diffusion requires roughly 17—percent turbulence, but
just which particular layer of the boundary flow is re-
sponsible for the rate of spread is not established. The
presence of velocity and turbulence gradients in all
directions makes even a visualization of the case diffi-
cult. The result is probably the aggregate effect of
many layers. The significant question at this stage in
the investigation, however, is whether any layers exist
with such an excessive magnitude of turbulence. The hot—
wire surveys not only answered this question in the af-
firmative but also revealed layers possessing considerably
more than the requisite 17—percent turbulence. It would
seem that a $9\frac{1}{2}^\circ$ angle of spread is quite in accord with the
hypothesis of transition by lateral contamination.

California Institute of Technology,
      Pasadena, California, November 1939.

APPENDIX A

RECENT NOTES ON TRANSITION BETWEEN LAMINAR AND
TURBULENT FLOW BY TRANSVERSE CONTAMINATION

By H. W. Liepmann

Recent measurements at the GALCIT have shown that the large fluctuations in the transition region of the boundary layer which have been observed in this paper as well as in reference 2 by Peters and by others indicate sudden changes in mean speed rather than turbulent fluctuations. To some extent this condition alters the aspect of the contamination effect, because these fluctuations cannot be assumed to be isotropic; in fact, the measurements show that the fluctuation components normal to the mean flow direction do not approach the values of 17 percent or more which were previously assumed.

It is believed that the contamination effect described in the main paper can be explained as a mixing rather than as a transport process in accordance with the following picture. Consider the boundary layer along a surface divided into two laterally contiguous regions in one of which the flow is laminar and in the other, turbulent. For purposes of visualization, the boundary between them might originally be considered as a plane perpendicular to the surface and parallel to the direction of mean flow. Because of the difference in shape between the laminar- and the turbulent-velocity profiles, the velocity in the fluid layers close to the surface will be higher in the turbulent than in the laminar boundary layer. In these layers then the phenomenon is essentially that of two adjacent, plane jets of fluid moving with different velocities. The mixing region between two such jets has been studied by Kuethe (see reference 3) and found to be wedge shape like the contamination region discussed herein. The experimentally found value for the angle of spread of contamination, $\tan \alpha = 0.17$, can be compared with the theoretical results of Kuethe for the mixing of two plane jets with velocities u_1 and u_2. According to Kuethe the limit of the mixing region is given by the expression

$$\tan \alpha = 0.0845 \times f(u_2/u_1)$$

where f is a certain function of the ratio u_2/u_1; and
the constant is determined from Goettingen measurements.
The experimentally found value, $\tan \alpha = 0.17$, requires·
$f \doteq 2$ or, according to Kuethe, $u_2/u_1 \doteq 0$. Hence, the
angle of spread is compatible with the mixing theory if
it is assumed that transition is caused mainly by the
mixing of the layers very close to the wall where
$u_2 \equiv u_{lam} \ll u_1 \equiv u_{turb}$. This assumption seems reasonable
because the angle of spread is a maximum for $u_2/u_1 = 0$,
and transition will probably occur along the outer edge
of the mixing region.

REFERENCES

1. Clauser, Milton, and Clauser, Francis: The Effect of
      Curvature on the Transition from Laminar to Turbu-
      lent Boundary Layer. T.N. No. 613, NACA, 1937.

2. Peters, H.: A Study in Boundary Layers. Proc. Fifth
      Int. Cong. Appl. Mech. John Wiley & Sons, Inc.,
      New York, 1939, pp. 393—395.

3. Kuethe, A. M.: Investigations of Turbulent Mixing
      Regions Formed by Jets. Jour. Appl. Mech., Vol. 2,
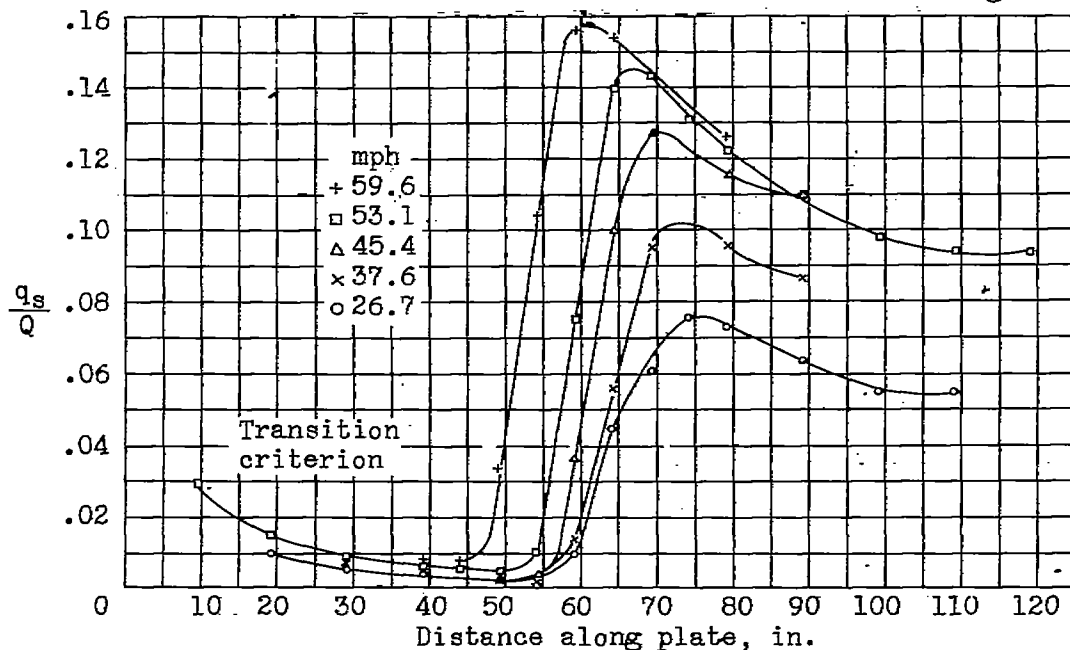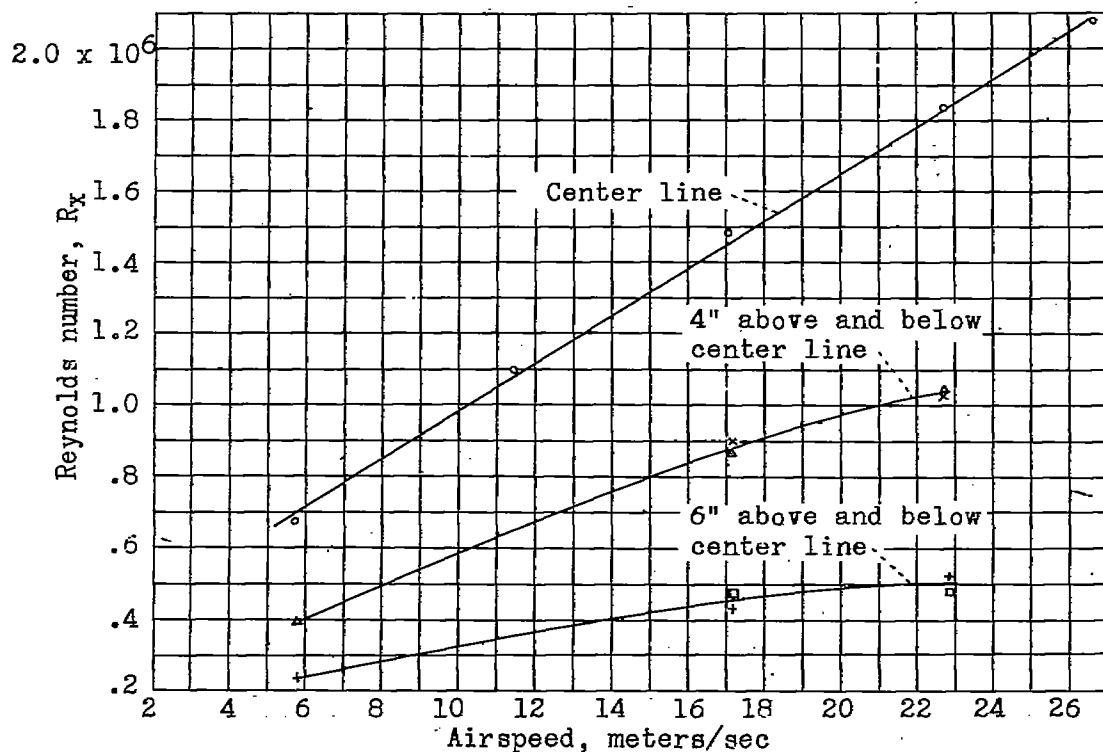   No. 3, Sept. 1935, pp. 87—95.

Figure 1.- Surface tube surveys along glass plate for a range of speeds. Stable pressure gradient. q_s = total pressure of surface tube, static pressure of free stream. Q = dynamic pressure of free stream.

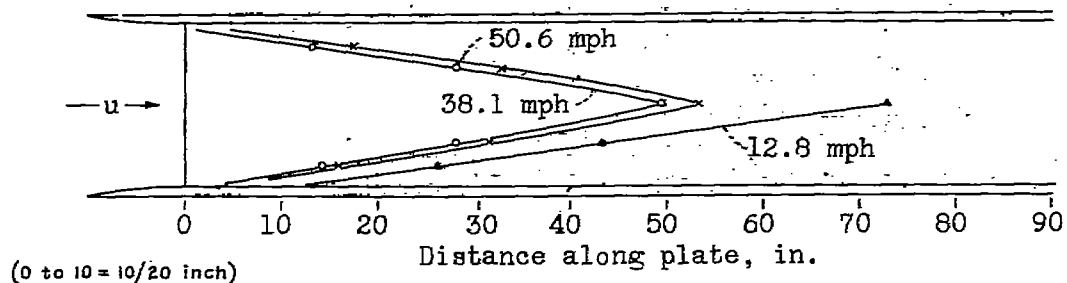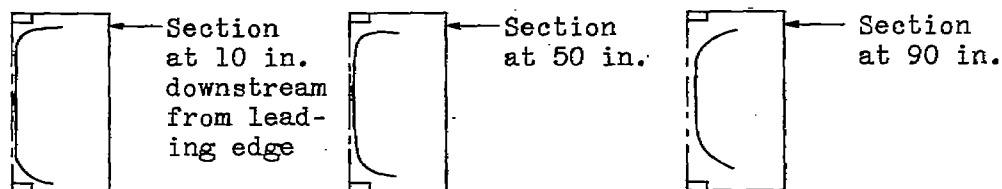Figure 2.- Variation of Reynolds number of transition with speed for different positions on glass plate.
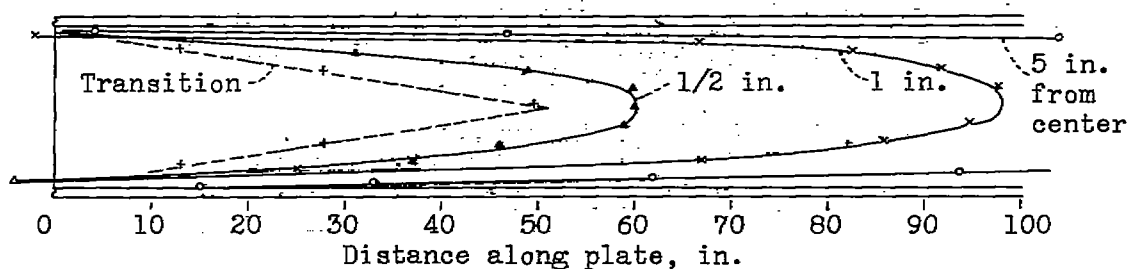
(0 to 10 = 10/20 inch)

Figure 3.- Map of transition showing effect of speed. Neutral pressure
gradient for 50.6 mph. Stable pressure gradient for 38.1 and 12.8 mph.

(a) Cross sections of half tunnel showing limit of boundary layer on
top, bottom, and plate.

(b) Contour map showing boundary layer limit.

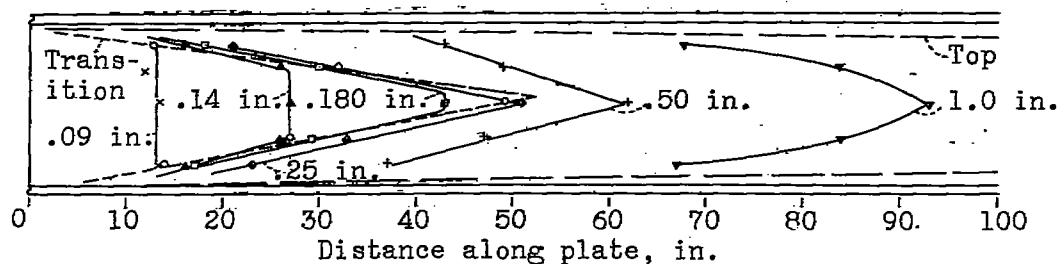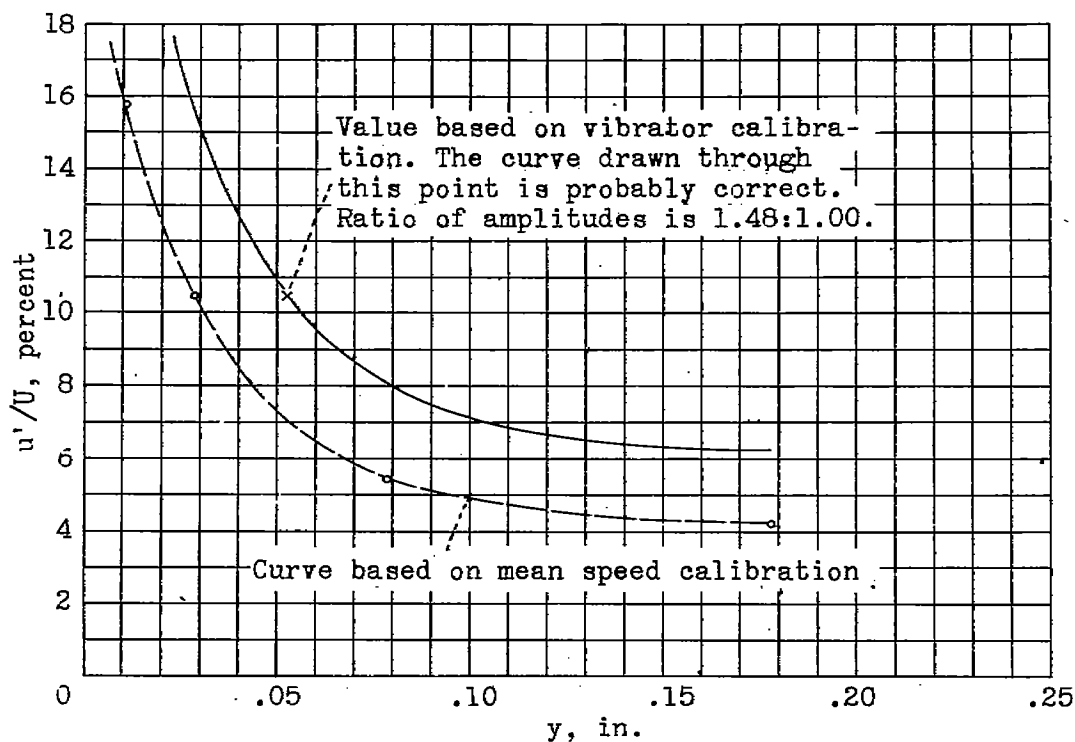Figure 4.- Composite diagram showing surveys.

Figure 5.- Contour map showing limit of boundary layer on glass plate.
Neutral pressure gradient; velocity = 51 mph; values of δ
defined by $u/U = 0.995$.

Value based on vibrator calibration. The curve drawn through this point is probably correct. Ratio of amplitudes is 1.48:1.00.

Curve based on mean speed calibration

(1 block = 10/50")

Figure 6.- Variation of maximum turbulence at transition with y based on survey along center line.

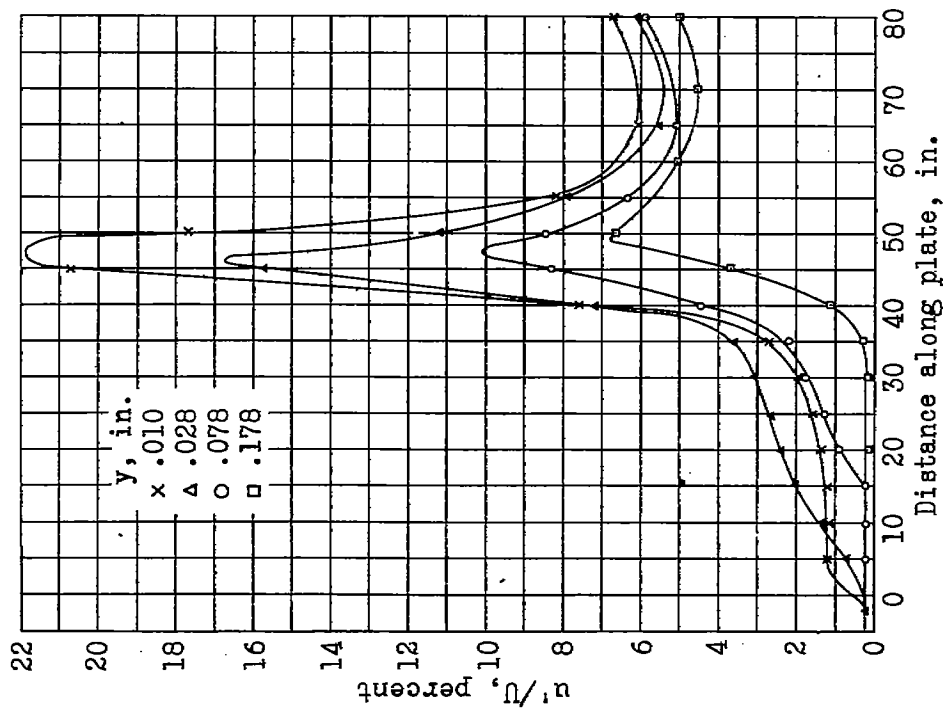y, in.
× .010
△ .028
○ .078
□ .178

Figure 7.- Turbulence surveys along plate, 2 in. above center line for different distances from the surface.

Figure 8.- Map of transition showing effect of
            false top spaced at different dis-
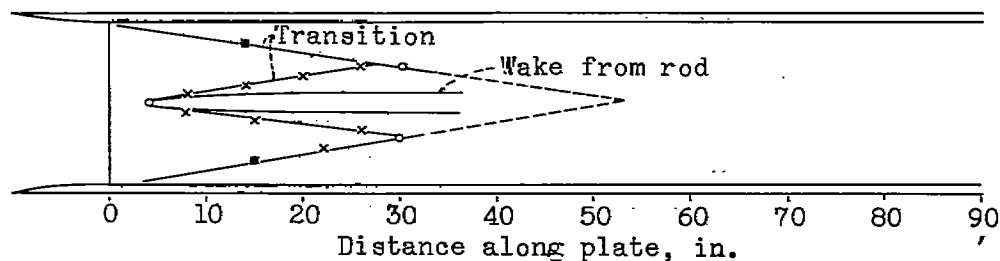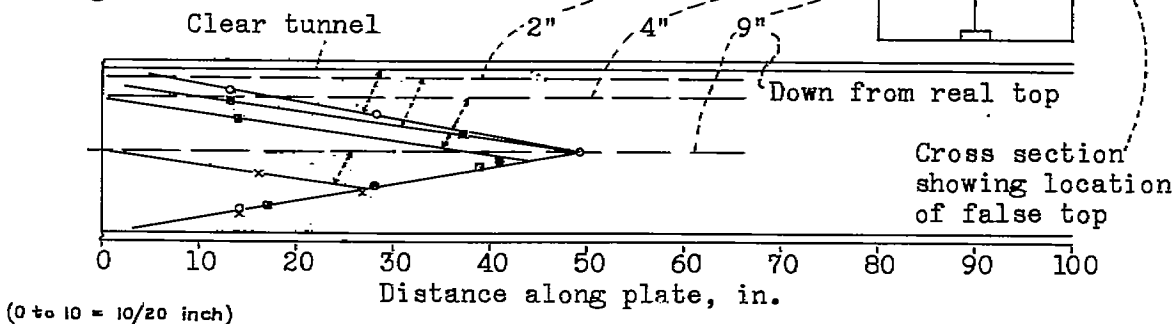tances from real top; velocity = 51 mph.

Configuration:

Clear tunnel   2"   4"   9"

Down from real top

Cross section
showing location
of false top

0   10   20   30   40   50   60   70   80   90   100
            Distance along plate, in.

(0 to 10 = 10/20 inch)

Transition
                        Wake from rod

0   10   20   30   40   50   60   70   80   90
            Distance along plate, in.

Figure 9.- Map of transition showing effect of blunt obstacle, 1/4" rod;
            velocity = 51 mph; neutral pressure gradient.

Transition
                        Wake from airfoil

0   10   20   30   40   50   60   70   80   90
            Distance along plate, in.
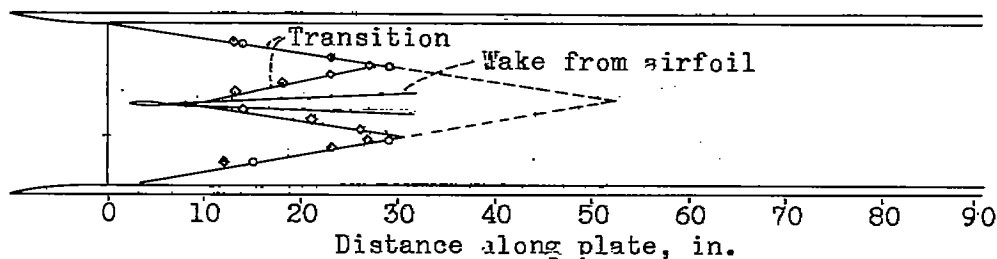
Figure 10.- Map of transition showing effect of streamline obstacle;
            double-arc 6 percent airfoil; velocity = 51 mph; neutral
pressure gradient.

                                34 mph
                                            24.1 mph
            51 mph

0   10   20   30   40
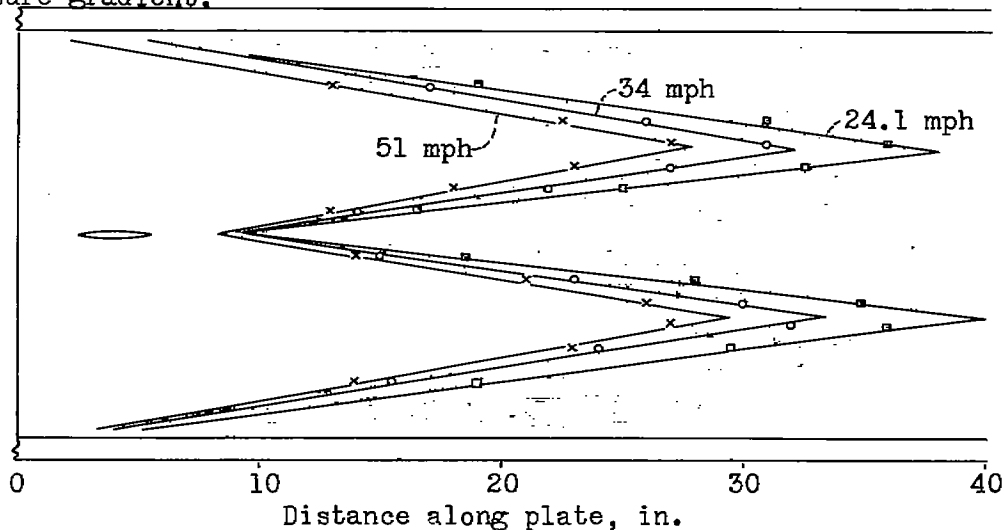   Distance along plate, in.

Figure 11.- Map of transition with streamline obstacle in place showing
            effect of speed.